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Repeatability of the Oxford Foot Model for Kinematic Gait Analysis of the Foot and Ankle

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Abstract

Introduction—Kinematic gait analysis via the multi-segmental Oxford foot model (OFM) may be a valuable addition to the biomechanical examination of the foot and ankle. The aim of this study is to assess the repeatability of the OFM in healthy subjects.

Methods—Nine healthy subjects, without a history of lower extremity injury, were recruited. Markers were placed according to the OFM requirements. Motion capture was conducted using the VICON NEXUS system on two separate test days, with two tests on each day conducted by two independent examiners. The range of motion (ROM) of the following inter-segments was selected for further analysis: forefoot-hindfoot, forefoot-tibia and hindfoot-tibia in frontal, sagittal and transverse planes. Each step was divided in two parts, a loading phase (from heel strike to midstance) and a push-off phase (from midstance to toe-off). The Intraclass correlation coefficient (ICC), standard error of the measurements with 90% confidence bounds (SEM_{90}) and the Minimal Differences needed to be considered real (MD) with 95% confidence interval were calculated for inter-observer and intra-observer and effect of trial using SPSS.

Results—There was a linear correlation between the number of trials and the ICC's (r^2=0.49, $p<0.001$), with six trial leading to good ICC's. Inter-observer repeatability: In the loading phase almost all ICC's were good or excellent (0.53–0.97) with only one parameter below 0.60. In the push-off phase two parameters scored moderate agreement, where the other 7 parameters had well to excellent agreement. The SEM_{90} values were varying from 0.85° to 2.49° in the loading phase and from 0.92° to 4.40° in the push-off phase. Intra-observer repeatability: In the loading phase all ICC's were good or excellent (0.71–0.97). In the push-off phase two parameters scored moderate agreement and the other 7 parameters had well to excellent agreement. The SEM_{90} ranged from 1.15° to 4.53° in the loading phase and in the push-off phase from 1.71° to 5.49°.

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The SEM_{90} values were varying from 0.85° to 2.49° in the loading phase and from 0.92° to 4.40° in the push-off phase. Intra-observer repeatability: In the loading phase all ICC's were good or excellent (0.71–0.97). In the push-off phase two parameters scored moderate agreement and the other 7 parameters had good to excellent agreement.

Conclusion—The repeatability analysis presented in this study provide excellent basis for objective measurement of the ankle and foot biomechanics. Results for inter-observer and intra-observer repeatability showed moderate to excellent ICC's and acceptable SEM_{90}. Best result were found in the sagittal plane (flexion/extension) followed by the frontal plane (abduction/adduction) and the transverse plane (inversion/eversion).

Keywords

Repeatability; Reproducibility; Reliability; 3D motion capture; Foot model

Introduction

Kinematic gait analysis is a more frequently used technique to objectively measure gait in healthy subjects and patients after foot and ankle trauma. Because of the intricate structure of the foot, models are more complex compared to knee and hip models and for reliable results a good repeatability is very important [1]. Nowadays multiple foot models are available and studies on gait of the foot and ankle in healthy subjects are increasing [2–17]. Knowledge concerning the biomechanics of the foot and ankle after injury is limited, although kinematic models can be very useful to compare joint function of healthy subjects with patients recovering from an injury of the foot and/or ankle [18,19]. An important prerequisite is that these models have a good repeatability for clinical applications [20–22].

Several multi-segmented models have been developed to study the biomechanical properties of the foot and ankle [23–26]. The Milwaukee foot model (MiFM), the Heidelberg foot measurement method (HFM), the Oxford foot model (OFM), 3D foot, Kinfoot and the Leardini foot model (LFM) are some examples, varying in number of segments, marker placement and total markers. Earlier repeatability studies for these multi-segmented models showed some good results [2,7,11,13,14,27–29]. The multi-segmented (OFM) has been reported as a valuable model to evaluate the biomechanical properties of the foot and ankle [30]. Carson et al., were the first to study the repeatability in a four- segmented model. Two healthy subjects were recruited and tested on several days by two examiners. They reported a 95% confidence interval of repeated measures between days ± 0.6° to ± 6.4° and between ratters ± 0.7° to ± 7.0° for the different outcome parameters [2]. For the OFM Curtis et al. performed a repeatability study in eight children and Wright et al. in 17 healthy subjects with mixed results. Nowadays studies with clinical applications are published referring to these repeatability studies. [20–22]. However these studies have some trivial points by using children, one observer and different statistical test. Therefore, there is place for a more detailed evaluation of the repeatability of the OFM in healthy subjects.

This study assessed the repeatability of the OFM in healthy adults. For this study healthy adults were analysed by more than one observer on separate days which was different compared to previous repeatability studies with the OFM [31–33]. This study also assessed the number of trials necessary in one single patient for good results. The result were presented with the intraclass correlation coefficient (ICC), standard error of the measurements with 90% confidence bounds (SEM_{90}) and the minimal differences needed to be considered real (MD) with 95% confidence interval [31,34]. The ROM between forefoot-hindfoot, forefoot-tibia and hindfoot-tibia was presented in this study, because of its clinically importance.

Methods

Study population

Randomly nine healthy subjects (eight males and one female; aged 21–57 years) were recruited for gait analysis of the foot and ankle. Exclusion criteria were a history of ankle or leg injuries/operations, anatomical abnormalities and spinal or neurological injury. All measurements were performed by two independent researchers. They were experienced with the OFM model by training. All subjects signed an informed consent. This study was approved by the medical ethics committee of the Maastricht University Medical Centre (MEC azM/UM).

Equipment

Motion capture was conducted using the VICON system (Vicon Motion Systems Ltd., Oxford, UK). The VICON-system comprised eight cameras (six MX3 and two T20 running at 200 Hz) connected with a computer. A force plate (Kistler 9282E) was used to identify the foot contact with the floor. Reflective markers were placed on specific points on the subjects with regular double sided tape. The placing of the markers was conducted according to the guidelines of the OFM (Table 1). Vicon NEXUS was used to visualize and process the 3D motions.

Protocol

All healthy subjects were measured at the human performance laboratory of Maastricht University on two separate days (three weeks interval). On each test day the subjects were analysed two times with at least one hour between the consecutive tests. The following characteristics were registered: age, weight, height, knee width (measured between the two condyles of the knee), ankle width (measured between the two malleoli of the ankle) and leg length (measured from the RASI/LASI marker to the LMMA/RMMA marker (Table 1). The markers were placed on both legs, following the specification of the OFM with double sided tape (Table 1). After placement of the markers the calibration started. At least one static trial was performed with all 41 markers, with subjects in an anatomic neutral position. Thereafter six markers were removed according to the protocol. These markers were: LMMA/RMMA (medial malleolus), LD1M/RD1M (Medial aspect of the distal 1st metatarsal) and LPCA/RPCA (Posterior calcaneus). Subsequently dynamic trials were conducted. The subjects were asked to walk barefoot at preferred ‘normal’ speed. First some practice trials were done. Subsequently, at least eight proper recordings were made during walking. Records were not used for further data output when patients failed to step in the middle of the force plate and when additional small or large steps were made to reach the force plate. The data of one whole step (heel strike or initial contact to toe-off) was divided in two intervals of

50%: the first interval of the step, the loading phase (initial contact/heel strike – midstance) and the second interval of the step, the push-off phase (midstance-toe-off). Files were saved for further data analysis. All subjects' right feet were measured for outcome parameters. Intersegment ROM parameters were analysed for the forefoot and hindfoot, forefoot and tibia and hindfoot and tibia in all the planes (sagittal, frontal and transverse, representing respectively flexion/extension, abduction/adduction and inversion/eversion) in the foot and ankle during walking [35,36] (Table 2). After the first session of this protocol performed by observer one all markers were removed. After one hour the second observer, blinded from the first, repeated the protocol.

The marker placement was performed with great care by the experienced observers. During calibrating in the stance phase axes of the knee and ankle were determined by the OFM model according the placement of markers. Small errors in these axes of the knee and ankle in stance phase can give error in the results. A small error in axes can lead to higher or lower flexion/extension between two segments and these errors can accumulate in ROM for abduction/adduction and inversion/eversion. This is caused by the manner of calculations of the ROM [35]. The important markers for the axes determination are placed on the side of each leg (LTHI/RTHI, LKNE/RKNE, LTIB/RTIB) and not linked to a specific anatomical bony landmark. Therefore the correct place for the markers is difficult to determine. By using the knee alignment correction in VICON NEXUS corrections in knee and ankle axes were performed to correct small mistakes, for a few millimetres [16]. The corrections were established after the recordings if axes were found to be incorrect by the examiner. The corrections were established in both static trials and dynamic trials. Axes in the dynamic trials were corrected on the moment of heel landing. Piazza et al. described an error which can occur when adapting these axes. The so called 'screw-home motion' of the knee can occur, when axes are incorrect. The axes of the knee can make a screw motion during gait leading to wrong results and errors [37]. All nine files of the nine healthy subjects were examined for the presence of this 'screw-home motion' during gait. None were found and all files of the healthy subjects were used for further data output.

Statistical analysis

The OFM gait analysis data were analysed with MATLAB (version 7.12, 2011) and SPSS (IBM Statistics, version 20). For every subject six successful trials were randomly chosen for final analysis. The ROM results were presented as mean ± standard deviation (SD) (minimum-maximum). The inter-observer and intra-observer repeatability analysis was performed by calculating the intraclass correlation coefficient (ICC3,k) with 95% confidence bounds (95%CI), the standard error of the measurements with 90% confidence bounds (SEM_{90}) and the minimal differences to be considered real (MD) with 95% confidence bounds. The ICC value revealed the quality of the test to distinguish subjects from each other. The ICC's were designated as <0.40 poor to fair agreement, 0.41–0.60 moderate agreement, 0.61–0.80 good agreement, and 0.81–1.00 excellent agreement [32]. The standard error of the measurements with 90% confidence bounds (SEM_{90}) reflected the error that can occur during measurements irrespective of high or low differences between subjects. The MD revealed when measurement are considered to be within or without expectations in repeated testing. The MD can be used to evaluate significant improvement in walking patterns in a single subject.

For the inter-observer repeatability ICC's, SEM_{90} and MD were calculated for each ROM parameter. The mean ROM for each parameter of all nine subjects of examiner one was compared with examiner two on the first day. The same was done for the second day. Both results for all parameters were presented as range. For the intra-observer repeatability results (between different days) ICC's, SEM_{90} and MD were calculated for all ROM parameters [38]. The means of examiner one for all ROM parameters of nine healthy subjects on the first day were compared with the means of examiner one on the second day. The same was done for examiner two. Both results for all parameters were presented as range. For the repeatability in number of trials only the ICC's were measured comparing two, four and six trials in all nine healthy subjects on the four walking moments and ICC's were presented as range [39].

Results

Subject characteristics

Nine healthy subjects (eight males and one female; aged 21–57 years) were included with a mean age of 26.3 ± 11.7 years. The average height was 1.79 m ± 0.07 m (range:1.69 m–1.88 m) and the average weight was 75.0 kg ± 11 kg (62 kg–90 kg)

In Table 3 the average ROM for the inter-segment angles of the forefoot-hindfoot, forefoot-tibia and hindfoot-tibia for the loading phase and the push-off phase during gait in every plane are presented.

Repeatability in number of trials

There was a linear correlation between the number of trials and the ICC's (r^2=0.49, $p<0.001$). The more recorded trials the better the ICC's. The results showed excellent ICC's for all the parameters using six trials, except for the ROM between the forefoot and tibia in the frontal plane (abduction/adduction) during loading phase with a lower border of the ICC range of 0.79 which was scored as good (Table 4). When using four trials all the parameters showed lower ICC's, however these were still good. ICC's were poor to fair results when using two trials. Therefore for further analysis at least six trials were taken.

Inter-observer repeatability

In the loading phase almost all ICC's were good or excellent (0.53–0.97). Only one parameter, the ROM between the forefoot and hindfoot in the frontal plane (abduction/adduction) was moderate with a lower border of the ICC below 0.60 (0.53–0.91). In the push-off phase two parameters scored moderate agreement, where the other 7 parameters had well to excellent agreement. These parameters were the ROM between the forefoot and hindfoot in the transverse plane (inversion/eversion) (0.19–0.64) and the ROM between the hindfoot and tibia in the transverse plane (inversion/eversion) (0.52–0.89) (Table 5) The SEM_{90} we're varying from 0.85° to 2.49° in the loading phase and from 0.92° to 4.40° in the push-off phase, indicating a small error of measurement [19]. The largest error of measurement was seen between the hindfoot-tibia in the frontal plane (abduction/adduction) during push-off phase. The MD ranged from 1.44° to 4.21° in the loading phase of gait and ranging from 1.94° to 7.65° in the push-off phase indicating that a large increase or decrease in ROM is necessary to see a significant difference in one healthy adult.

Intra-observer repeatability (between different days)

In the loading phase all ICC’s were good or excellent (0.71–0.97). In the push-off phase two parameters scored moderate agreement and the other 7 parameters had good to excellent agreement. These parameters were the ROM between the forefoot and tibia in the transverse plane (inversion/eversion) (0.50–0.68) and the ROM between the hindfoot and tibia in the transverse plane (inversion/eversion) (0.46–0.75) (Table 5) In the loading phase the SEM_{90} ranged from 1.15° to 4.53° and in the push-off phase of gait from 1.71° to 5.49°. As seen in the inter-observer repeatability parameters with a high ROM, for example the ROM between the forefoot and tibia in the sagittal plane (flexion/extension) had a higher error of measurement. However also in the ROM between the forefoot and tibia and hindfoot and tibia in the transverse plane during push-off phase high standard error of measurement were found, while the ROM is relatively low. The MD’s ranged from 1.55° to 6.49° in the loading phase of gait and ranging from 2.88° to 9.29° in the push-off phase.

In general the ICC’s, SEM_{90} and MD for the inter-observer repeatability were better compared to the intra-observer repeatability. ICC’s were almost for all parameters good to excellent except for a few parameters especially in the transverse plane. The SEM_{90} and MD were low for almost all parameters with a low ROM and high in parameters with a high ROM.

Discussion

The aim of this study was to analyse the repeatability of the OFM. For the repeatability in number of trials there was a significant correlation in number of trials and ICC’s. The results showed excellent ICC’s for almost all parameters using six trials. For inter-observer and intra-observer repeatability almost all ICC’s were good to excellent and SEM_{90}, MD were low in parameters with a low ROM and high in parameters with high ROM. Overall the repeatability showed moderate to excellent results with acceptable error.

For the inter-observer repeatability the ROM between the forefoot and hindfoot in the frontal plane (abduction/adduction) during loading phase (0.53–0.91), the forefoot and hindfoot in the transverse plane (inversion/eversion) (0.19–0.64) and the ROM between the hindfoot and tibia in the transverse plane (inversion/eversion) (0.52–0.89) during push-off phase were below 0.60. For the intra-observer repeatability the ROM between the forefoot and tibia in the transverse plane (inversion/eversion) (0.50–0.68) and the ROM between the hindfoot and tibia in the transverse plane (inversion/eversion) (0.46–0.75) during push-off phase were below 0.60. The ROM between the hindfoot and tibia in the transverse plane (inversion/eversion) during push-off phase was the only parameter below 0.60 in both inter-observer and intra-observer repeatability results, however in both inter-observer and intra-observer results the higher border of the range was above 0.60. The highest SEM_{90} for the inter-observer repeatability was seen between the hindfoot and tibia in the frontal plane (abduction/adduction) during push-off phase varying from 2.80° to 4.40°. McGinley et al. state in their review that in common clinical situations an error of 2° or less is highly likely to be considered acceptable. Errors between 2° and 5° are also likely to be regarded as reasonable but may require consideration in data interpretation [19].

In the intra-observer repeatability only two parameters had a standard error of measurement above five degrees. These were the ROM between the forefoot and tibia in the sagittal plane (flexion/extension) during push-off and between the forefoot and tibia in the transverse plane (inversion/eversion) in the push-off phase. In these parameters the error range was high; however in these two parameters the ROM in healthy subjects was high with an average of 16 and 29 degrees. The error is expected to be higher in parameters with a high ROM and lower in parameters with a low ROM. Therefore the SEM_{90} for each parameter where compared with the total ROM. A few parameters were found to have a higher percentage of error compared to others. The ROM between the forefoot and hindfoot in the frontal plane (abduction/adduction) during loading phase and the ROM between the forefoot and hindfoot in the transverse plane (inversion/eversion) during push-off phase. For both parameters the error accounted for more than 40% of the total ROM. Also the ROM between the hindfoot and tibia in the transverse plane during push-off phase had a relative high ROM. For the other parameters SEM_{90} and MD were low for parameters with a low ROM and high in parameters with a high ROM. Small errors in marker placement can lead to deviating flexion/extension ROM in the sagittal plane between two segments and these errors can accumulate in ROM for abduction/adduction in the frontal plane and inversion/eversion in the transverse plane [35]. Therefore best ICC's are expected in the sagittal plane and the ICC's in the frontal (abduction/adduction) and transverse plane (inversion/eversion) will be lower as seen in this study.

Overall three parameters had both high error of measurements and lower ICC's compared to other parameters. These were the ROM between the forefoot and hindfoot in the frontal plane (abduction/adduction) during loading phase, the ROM between the forefoot and hindfoot in the transverse plane (inversion/eversion) and the ROM between the hindfoot and tibia in the transverse plane (inversion/eversion) during push-off phase. Although these errors were acceptable and therefore can be used for analysing biomechanics of the foot and ankle but needs attention.

Through the last decades many different multi-segment protocols and models for the kinematic analysis of the foot have been designed [2–16]. The results of the current study are comparable to others studies to the repeatability of the OFM. Carson et al. analysed the repeatability in a four- segmented model. Two healthy subjects were recruited and tested on several days by two examiners. They reported a 95% confidence interval of repeated measures between days of ± 0.6° to ± 6.4° and between ratters of ± 0.7° to ± 7.0° for the different outcome parameters. (2) They found the highest differences in forefoot and hallux. The current study did not analyse the hallux, but also found high standard error of measurements in some forefoot-hindfoot parameters. Curtis et al. performed a repeatability study in eight children who were tested twice on two separate days at their gait laboratory. The found small differences in means between test days, varying from 0.3° to 1.9°. They found ICC's were varying from −0.14 to 0.96. Overall ICC's were lower compared to this study. They found absolute repeatability was best in the sagittal plane followed by the frontal plane and the transverse plane, as was seen in this study [28]. Wright et al. analysed 17 healthy subjects in two sessions on one day with the four-segmented OFM by one observer. They observed the forefoot and hindfoot angles during walking with and without referencing to neutral stance. Intraclass correlation coefficients and standard errors of measurements were calculated for the different outcome parameters. They found acceptable to good repeatability (ICC>0.83) and small error (<2.45°) in the hindfoot and forefoot in all angle planes during gait referencing to neutral stance. However, without referencing to neutral stance repeatability was less (ICC>0.38) with a large error (<5.09°), especially in frontal plane [30]. They also found best repeatability in the sagittal plane, followed by the frontal plane and transverse plane as found in this study.

Some limitations should be considered when appreciating these results. For this study patient with an age between 21 to 57 years were analysed. Biomechanics of elderly people may differ from young people. Therefore this study reflects a good view on the biomechanics in healthy adults. Younger and older patients can have different ROM results in the foot and ankle. The number of subjects in this study was low but is comparable with other repeatability studies. Another limitation is the placement of markers on the same day by two different observers. The first observer placed the markers according to the OFM protocol and removed these markers after his measurement. However this double sided tape can leave some signs on the skin. Therefore the second observer could not be 100% blinded. This led to better inter-observer repeatability results compared to the intra-observer repeatability results. Another point was the correction of ankle and knee axes using the knee alignment device in VICON NEXUS. Small errors in these axes of the knee and ankle in stance phase can give error in the results. A small error in axes can lead to higher or lower flexion/extension between two segment and these errors can accumulate in ROM for abduction/adduction and inversion/eversion. When using this device small errors in maker positions are corrected leading to higher ICC’s and lower SEM_{90}. Besides marker placement tissue artefacts are important for errors in results.

Conclusion

The repeatability analysis presented in this study provides a good basis for objective measurement of the ankle and foot biomechanics. Results for inter-observer and intra-observer repeatability showed moderate to excellent ICC’s and acceptable SEM_{90}. Best result were found in the sagittal plane (flexion/extension) followed by the frontal plane (abduction/adduction) and the transverse plane (inversion/eversion).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Marker placement.

Markers: Total of 41; 1 Centred and 20 Bilateral	
Marker diameter: 15 mm.	
Name	**Placing**
SACR	Sacral marker: middle of sacrum
RTHI/LTHI	Thigh: half of a straight line between major trochanter and RKNE/LKNE
RASI/LASI	Anterior iliac spine
RKNE/LKNE	Knee: lateral joint space of the knee
RHFB/LHFB	Head Fibula: placed directly on the proximal head of the fibula
RTUB/LTUB	Tuberosity: tuberosity of the tibia
RTIB/LTIB	Tibia: lateral on a straight line between marker RKNE/LKNE and RANK/LANK
RSHN/LSHN	Shin: anterior on the middle of the tibia
RPCA/LPCA	Posterior calcaneus
RANK/LANK	Ankle: lateral malleolus
RMMA/LMMA	Medial malleolus: medial aspect on malleolus
RCPEG/LCPEG	Wand marker on the heel pointing in cranial direction
RHEE/LHEE	Heel: on the most distal aspect of the heel
RSTAL/LSTAL	Sustentaculum tali
RLCA/LLCA	Lateral calcaneus
RP5M/LP5M	Proximal 5th metatarsal: lateral aspect
RD5M/LD5M	Distal 5th metatarsal: lateral aspect
RTOE/LTOE	Toe: on dorsum of the foot between phalanges 2 and 3
RHLX/LHLX	Base of hallux
RD1M/LD1M	Medial aspect of the distal 1st metatarsal
RP1M/RP1M	Medial aspect of the proximal 1st metatarsal

Table 2

Motions.

	Loading phase	Push-off phase
Forefoot-hindfoot		
Sagittal plane (flexion/extension)	Dorsiflexion	Dorsiflexion
Frontal plane (abduction/adduction)	Abduction	Abduction
Transverse plane (inversion/eversion)	Supination	Supination
Forefoot-tibia		
Sagittal plane (flexion/extension)	Dorsiflexion	Dorsiflexion
Frontal plane (abduction/adduction)	Abduction	Abduction
Transverse plane (inversion/eversion)	Inversion	Inversion
Hindfoot-tibia		
Sagittal plane (flexion/extension)	Dorsiflexion	Dorsiflexion
Frontal plane (abduction/adduction)	Abduction	Abduction
Transverse plane (inversion/eversion)	Inversion	Inversion

Table 3

ROM averages for nine healthy subjects on four measure moments.

Loading phase				
	Day 1 Examiner 1	**Day 1 Examiner 2**	**Day 2 Examiner 1**	**Day 2 Examiner 1**
Forefoot-hindfoot				
Sagittal plane (flexion/extension)	8.54 ± 2.52 (5.95–11.99)	8.59 ± 2.6 (5.22–11.77)	9.25 ± 3.86 (5.95–16.69)	8.97 ± 3.97 (4.43–16.17)
Frontal plane (abduction/adduction)	4.21 ± 1.13 (2.33–5.35)	4.40 ± 1.31 (2.55–6.28)	4.95 ± 1.13 (3.14–6.98)	4.74 ± 1.07 (2.51–6.19)
Transverse plane (inversion/eversion)	7.17 ± 1.17 (5.25–8.77)	8.05 ± 1.83 (5.78–10.66)	7.83 ± 2.02 (4.76–12.14)	7.92 ± 2.50 (4.33–13.34)
Forefoot-tibia				
Sagittal plane (flexion/extension)	14.68 ± 2.82 (11.11–18.81)	15.23 ± 2.90 (9.74–19.01)	14.68 ± 2.59 (9.13–18.70)	15.12 ± 2.80 (8.16–17.55)
Frontal plane (abduction/adduction)	15.92 ± 4.12 (10.01–22.16)	15.99 ± 3.54 (11.76–21.07)	16.67 ± 3.46 (11.97–24.26)	16.84 ± 2.59 (13.68–21.00)
Transverse plane (inversion/eversion)	9.41 ± 3.02 (6.57–16.08)	10.21 ± 2.65 (6.29–15.00)	10.13 ± 2.32 (6.11–13.42)	10.79 ± 2.23 (7.78–13.39)
Hindfoot-tibia				
Sagittal plane (flexion/extension)	10.97 ± 2.94 (7.18–15.40)	10.84 ± 3.27 (6.76–15.75)	12.02 ± 2.34 (8.68–16.17)	11.94 ± 2.64 (7.94–15.78)
Frontal plane (abduction/adduction)	13.55 ± 3.15 (9.11–18.95)	14.03 ± 3.02 (9.21–17.52)	15.30 ± 3.03 (10.98–21.37)	15.15 ± 3.18 (11.26–22.80)
Transverse plane (inversion/eversion)	5.99 ± 2.45 (2.36–10.17)	6.29 ± 2.06 (3.81–10.05)	6.63 ± 1.42 (4.48–8.49)	6.67 ± 1.86 (2.63–9.28)
Push-off phase				
	Day 1 Examiner 1	**Day 1 Examiner 2**	**Day 2 Examiner 1**	**Day 2 Examiner 1**
Forefoot-hindfoot				
Sagittal plane (flexion/extension)	17.76 ±4.37 (11.33–26.04)	18.49 ± 5.24 (11.13–26.19)	18.29 ± 5.95 (9.57–26.42)	17.44 ± 4.60 (8.64–24.17)
Frontal plane (abduction/adduction)	11.67 ± 2.28 (8.90–14.94)	11.82 ± 3.46 (7.05–17.98)	11.61 ± 2.63 (7.92–14.24)	12.30 ± 2.96 (7.59–16.08)
Transverse plane (inversion/eversion)	7.42 ± 2.18 (4.76–10.65)	8.70 ± 1.95 (5.65–11.77)	9.05 ± 2.89 (5.88–13.86)	9.51 ± 2.17 (6.35–13.20)
Forefoot-tibia				
Sagittal plane (flexion/extension)	29.07 ± 6.26 (19.97–41.40)	29.90 ± 6.11 (24.32–42.00)	30.62 ± 7.39 (20.45–41.13)	29.65 ± 6.35 (20.72–39.20)
Frontal plane (abduction/adduction)	13.51 ± 5.38 (5.41–22.11)	13.92 ± 5.11 (7.62–22.05)	14.78 ± 5.16 (8.62–24.95)	14.48 ± 5.83 (7.77–25.95)
Transverse plane (inversion/eversion)	15.39 ± 4.78 (11.24–24.18)	16.96 ± 3.68 (12.38–24.13)	16.67 ± 2.62 (12.19–19.98)	16.52 ± 2.97 (11.98–21.24)
Hindfoot-tibia				
Sagittal plane (flexion/extension)	12.19 ± 3.13 (8.54–16.93)	12.59 ± 2.88 (9.62–19.01)	13.03 ± 3.69 (7.95–19.83)	12.70 ± 4.08 (6.75–18.84)
Frontal plane (abduction/adduction)	11.54 ± 2.58 (7.51–14.85)	12.12 ± 3.05 (6.13–16.05)	11.08 ± 2.89 (6.86–14.92)	10.78 ± 3.79 (5.85–18.52)
Transverse plane (inversion/eversion)	9.87 ± 3.07 (3.53–14.98)	10.09 ± 3.28 (4.56–15.98)	9.58 ± 2.58 (6.26–13.40)	9.32 ± 2.39 (4.67–11.77)

Table 4

Repeatability in number of trials with ICC's.

	2 Trials	2 Trials	4 Trials	4 Trials	6 Trials	6 Trials
	Load phase	**Push-off phase**	**Load phase**	**Push-off phase**	**Load phase**	**Push-off phase**
	ICC range	**ICC range**	**ICC range**	**ICC range**	**ICC range**	**ICC range**
Forefoot-hindfoot						
Sagittal plane (flexion/extension)	0.93–0.97	0.92–0.97	0.96–0.98	0.97–0.98	0.97–0.98	0.98–0.99
Frontal plane (abduction/adduction)	0.26–0.82	0.49–0.96	0.66–0.93	0.82–0.94	0.79–0.93	0.93–0.98
Transverse plane (inversion/eversion)	0.16–0.88	0.81–0.91	0.70–0.93	0.92–0.97	0.84–0.95	0.90–0.97
Forefoot-tibia						
Sagittal plane (flexion/extension)	0.88–0.95	0.89–0.97	0.91–0.97	0.95–0.97	0.96–0.98	0.96–0.99
Frontal plane (abduction/adduction)	0.83–0.93	0.94–0.96	0.84–0.97	0.97–0.98	0.87–0.98	0.99–0.99
Transverse plane (inversion/eversion)	0.66–0.90	0.94–0.98	0.89–0.97	0.97–0.99	0.91–0.97	0.98–0.99
Hindfoot-tibia						
Sagittal plane (flexion/extension)	0.91–0.99	0.77–0.92	0.96–0.99	0.92–0.95	0.98–0.99	0.95–0.97
Frontal plane (abduction/adduction)	0.60–0.86	0.79–0.93	0.87–0.94	0.88–0.96	0.93–0.96	0.94–0.96
Transverse plane (inversion/eversion)	0.74–0.95	0.70–0.93	0.83–0.97	0.95–0.96	0.89–0.98	0.96–0.97

Table 5

Inter-observer and intra-observer repeatability.

Inter-observer repeatability						
Loading phase				**Push-off phase**		
	ICC range	**SEM_{90} variability (deg)**	**MD variability (deg)**	**ICC range**	**SEM_{90} variability (deg)**	**MD variability (deg)**
Forefoot-hindfoot						
Sagittal plane (flexion/extension)	0.93–0.96	1.57–1.82	2.66–3.08	0.81–0.92	2.15–3.39	4.66–5.93
Frontal plane (abduction/adduction)	0.53–0.91	0.85–1.75	1.44–2.97	0.73–0.89	0.92–1.46	3.63–4.43
Transverse plane (inversion/eversion)	0.84–0.96	1.05–1.49	1.77–2.52	0.19–0.64	3.05–3.53	3.33–4.6
Forefoot-tibia						
Sagittal plane (flexion/extension)	0.95–0.95	1.41–1.49	2.28–2.52	0.74–0.83	2.74–3.20	5.43–7.65
Frontal plane (abduction/adduction)	0.92–0.94	2.00–2.18	3.38–3.69	0.72–0.89	2.94–3.84	3.58–3.71
Transverse plane (inversion/eversion)	0.88–0.91	1.60–2.31	2.72–3.91	0.74–0.90	1.80–3.21	2.47–6.38
Hindfoot-tibia						
Sagittal plane (flexion/extension)	0.95–0.97	1.25–1.30	2.11–2.19	0.84–0.85	2.44–2.82	3.74–6.15
Frontal plane (abduction/adduction)	0.88–0.95	1.61–2.49	2.72–4.21	0.64–0.86	2.80–4.40	1.94–3.24
Transverse plane (inversion/eversion)	0.65–0.95	1.18–2.26	2.00–3.83	0.52–0.89	1.56–3.17	3.05–3.80
Intra-observer repeatability						
	Loading phase			Push-off phase		
	ICC range	SEM_{90} variability (deg)	MD variability (deg)	ICC range	SEM_{90} variability (deg)	MD variability (deg)
Forefoot-hindfoot						
Sagittal plane (flexion/extension)	0.92–0.94	2.76–3.51	3.63–5.74	0.89–0.91	3.64–3.82	6.15–6.46
Frontal plane (abduction/adduction)	0.84–0.90	2.15–2.62	1.55–2.47	0.82–0.91	1.71–3.18	2.88–5.38
Transverse plane (inversion/eversion)	0.71–0.89	1.97–2.72	5.16–5.96	0.62–0.63	2.97–3.85	5.00–6.51
Forefoot-tibia						
Sagittal plane (flexion/extension)	0.92–0.95	3.21–4.53	4.63–5.41	0.89–0.92	4.08–5.30	6.9–8.95
Frontal plane (abduction/adduction)	0.97–0.97	2.12–2.20	4.96–6.49	0.94–0.94	3.02–3.12	5.10–5.27
Transverse plane (inversion/eversion)	0.86–0.95	1.46–3.77	3.05–5.43	0.50–0.68	5.13–5.49	8.68–9.29
Hindfoot-tibia						

Inter-observer repeatability						
Loading phase				Push-off phase		
	ICC range	SEM_{90} variability (deg)	MD variability (deg)	ICC range	SEM_{90} variability (deg)	MD variability (deg)
Sagittal plane (flexion/extension)	0.73–0.94	2.21–3.64	4.13–4.77	0.65–0.76	3.92–4.84	6.62–8.18
Frontal plane (abduction/adduction)	0.94–0.97	1.15–1.92	4.74–7.43	0.63–0.81	2.79–4.95	4.71–8.37
Transverse plane (inversion/eversion)	0.85–0.94	1.80–2.25	2.63–5.35	0.46–0.75	3.30–4.94	5.57–8.34